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IONOSPHERIC EFFECTS ON GPS SIGNAL IN LOW-LATITUDE REGION: A CASE STUDY REVIEW OF SOUTH EAST ASIA AND AFRICA

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ABSTRACT

The ionosphere is a significant source of errors affecting L-Band (1-2 GHz) signal propagation using Global Position System (GPS). The propagated GPS signals that passes through the Earth's atmosphere where affected by ionosphere and troposphere irregularities and caused the signal propagation delay. However, the velocity of signals that propagate within the atmosphere deviates from vacuum line of sight (LOS), while the refractivity of ionosphere and troposphere influence the signal propagation delay causing atmospheric effects due to high electrons density. Both affect the signal in different ways due to their particular refractive properties. The review focuses of some of the previous research studies conducted on empirical modeling of the ionospheric effect in low latitude region. The tabulated findings of such models presented in this article.

Keywords: *Low-latitude, ionospheric effect, GPS, TEC, SNR*

1. INTRODUCTION

The launching of 24 NAVISTAR satellites was completed by U.S Air force on 26th June 1993 and the network of these satellites is called Global Positioning System (GPS). These NAVSTAR satellites were designed by Rockwell International. Initially, the operation started in 8th December 1993, but full functioning commenced on 27th April 1995[1]. The orbits inclined at about 55^o to the equatorial plane and is located approximately 20,183 km above the earth's surface[1], [2]. The network of these satellites provides continuous 24 hours coverage to all parts of the globe. GPS has been under development, operated, and maintained by the U. S. Department of Defense (DoD). Because of its uniqueness and its potential applications, particularly related to mobile users, the NAVSTAR GPS deserves particular attention especially the ionospheric nature that cause signal fading. The signals could be intersperse with interfering signals. However, GPS link is more likely to be susceptible to limiting conditions. Such as rain attenuation, multipath fading, shadowing effect, Doppler shift, interference and ionosphere scintillation [4]–[6]. In this research review, only ionospheric effect for open space signals will be considered.

GPS provides special coded satellite signals that will be processed by GPS receivers and enabling them to compute position, speed and time. The Precise Point Positioning (PPP) for GPS tasks using four mobile satellite signals to compute positions in three dimensions in the receiver clock. GPS provides accurate locations, time information at a particular precise position at all different weather around the world [7]–[9].

Using the GPS dual frequencies receiver system to eliminate ionospheric delays provides a useful tool for measuring the ionospheric total electron content (TEC). Atmosphere becomes an important medium for the GPS signal communication path, but ionospheric effect degrades the signal as a result of fading effect and presence of much electrons contents. These electrons densities will cause the scintillation effect [10]–[12].

This literature studies will focus on the past and present ionospheric studies conducted in the low-latitude regions, given much emphasis on some part of South-East Asia and Africa regions.

2. IONOSPHERIC EFFECT

GPS signals that transmit from the satellite at a distance of 20,183 km, passes through a vacuum until they reach

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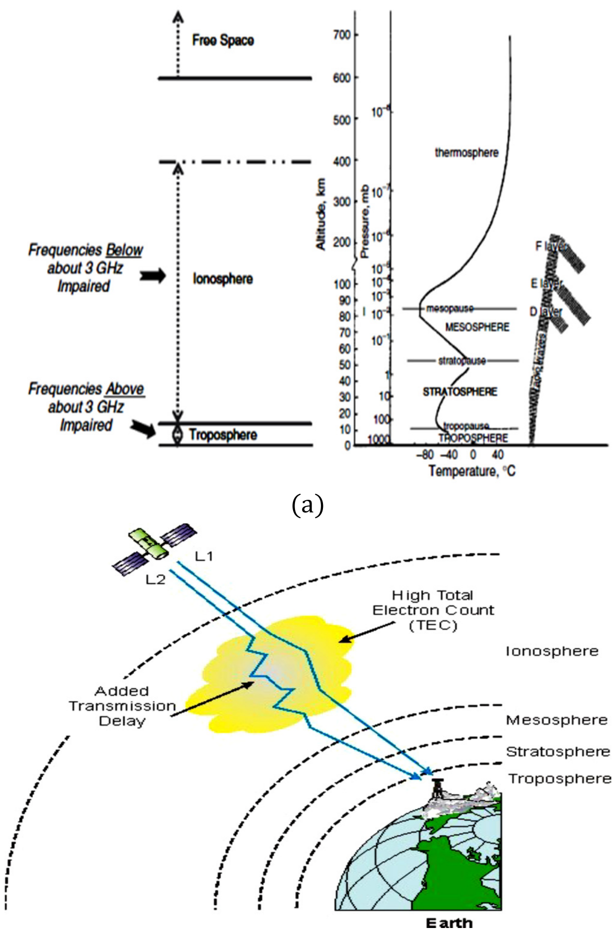
the last few percent of their journey. The signals encounter the bulk of free electrons around 350 km, and it is these particles that affect the speed at which the signal propagates [6], [13]. The signals travel at a velocity of light through space, but they are slowed slightly by varying degrees in direction as they pass through the ionosphere [7], [14]. Regular and unusual solar activity can produce variations in the effect of the ionosphere on GPS signals results in errors at atmospheric height of about 100 km. Figure 1 shows the ionosphere region according to the height. The receiving signals will cause the receiver to have ranging errors such as ephemeris data, satellite clock, pseudo-range and multipath.



(a)

(b)

Figure 1 (a) The Vertical height of Ionosphere F, E and D region and (b) Signal affected at ionosphere region[15].

Radio waves propagation passing through the ionospheric region was described by Appleton-Hartee formula[16], [17] of ionospheric refractive index and group delay. The delays can be summarized as:

• Propagation that causes signals delay in the presence of ionosphere results in increased errors in position and navigation Scintillation effects caused losses of signal due to small-scale irregularities in the ionosphere.

The ionospheric errors equations GPS approach can be written as

$$\mu = 1 - a\frac{N}{f^2} \qquad (1)$$

and $\alpha = 40.3m^2s^{-2}$ N; denotes the free electrons density per cubic meter $\dot{\mu}_i$, is the ionospheric group delat with respect to propagation in vacuumand f is the radiowave frequency in *GHz.* Note that, effect of ionospheric refraction index is inversely proportional to the square frequency that causes a delay in time Δt that is:

$$\Delta t_i = \frac{1}{c}\int_T^R \left(\dot{\mu i} - 1\right) dl = \frac{1}{c} * \frac{a}{f^2}\int_T^R N dl \qquad (2)$$

The quantity Ndl is the Total Electron Content (TEC), in electrons per square meter, integrated along the signal path between transmitter *(T)* and receiver *(R)*,*C* is the speed of light. In carrier phase measurements, the effect causes a phase advance leading to an underestimated (shorter) range

Some previous measurements were done by other researchers utilizing the Faraday's rotation using linearly polarized equation signal delay and the circularly polarized GPS signal [17][18]. Therefore the frequency delay can be rewrites as follows:

$$\Delta t_{phase} f \frac{40.3TEC}{f^2} \leq 0 \qquad (3)$$

whereby the time delay can be expressed using phase change multiplied by the frequency in radian/second.

$$\Delta\phi 2\pi f\tau = 2\pi\frac{k}{f} = 4\pi^2\frac{k}{w} \qquad (4)$$

The ionospheric effect observables equation is given by Pseudo-range,

$$\psi = p + d_{Igr} + d_I^{len} = P + \frac{P}{f^2} + \frac{q}{f^3} + \frac{u}{f^4} + d_I^{ler.} \qquad (5)$$

Phase is

$$\phi = P - d_I^{len} = P - \frac{P}{f^2} + \frac{q}{f^3} + \frac{u}{f^4} + d_I^{ler.} \qquad (6)$$

where f is the signal frequencies for GPS L1 and L2 ($f = 1.2276GHz$ *and* $f = 1.57542\ GHz$), d_{Igr} is the group delay, d_I^{len} is excess path length of the signal,u is the electron concentration at slant height, q is the instrumental biases and P is the distance on geometric between satellite and the receiver[19].

2.1 Ionospheric Parameter

Tabulated results in Table 1 obtained from the research conducted at different locations for different years provides summary of ionospheric disturbances affecting these areas. The effects were investigated using Ionos TEC equipment having dual frequency receiver at a vertical height of 400 km in 2005 by Rashim Wahi, utilized TEC data and frequency rate of 0.5 Hz [20]. A research conducted on the ionospheric effect on a Malaysian atmosphere by varying the TEC according to the height using the IONosphere map Exchange (IONEX) data and show the total electrons content affecting the radio signals [21]. Ya'acob in model prediction of ionospheric effect utilizes the Jones 3-D ray tracing and Nequick International software[22]. The model can be used to get differential ionospheric delay in sub-centimetre accuracy. Therefore, the model was suitable only for short baseline prediction and single frequency users.

The studies of ionospheric disturbances were carried out in 2010 using commercial handheld GPS receiver by Abba et al., analyzing the Signal to Noise Ratio (SNR) with respect to elevation angles and azimuth angles of received propagations GPS signal. Ionospheric effect observed on some Pseudorandom noise code (PRN)s orbiting the sky of Samarahan as shown in Figure 2 for the PRN 15 indicating the fading of the received SNR signal. Similar study of ionospheric effects on GPS propagation signal was also conducted using logarithmic and polynomial regression model by [5] in Samarahan Malaysia, whereby the model of cumulative frequency function (CDF) shows, some satellites experienced signal fading on 3rd February and 12th March 2010 as shown in Figure 3. Using single frequency handheld GPS receiver data, the analysis shows that PRN 9[23] and PRN 14 were affected by ionospheric disturbances (Figure 3). The ionospheric irregularities at equatorial region occur more than 40% of the year at 20.00 LT to 02.00 local time (LT) by Li et al., 2009 [24][25].

In 2012, an analysis of ionospheric effect was done by [26] in Hong Kong, evaluating the signal intensity (SI) from the narrowband power (NBP) and wide band power (WBP) using the parameters of phase and amplitude scintillation. The ionospheric disturbances affect more than eight satellites whereby PRN 15 has the highest impact of the amplitude scintillation effect. Table 2 summarizes the affected PRNs Mobile Satellites (MS) signal. Simultaneous observations were conducted on the ionospheric anomalies by [27] in low latitude African region, and some MS was affected which includes PRN 6, PRN 15 and PRN 24. These cause massive fading for the signals. Ionospheric anomalies studies conducted at Asia low latitude region of by [28] analyzed 2004 GPS data taken from the reference stations and found out that MS for PRN 1 S4 index was high at that particular local time

Table 1: Some models error on ionospheic studies conducted at low latitude regions of South East Asia and Africa

Year carried out	Region	Techniques / Model applied	Parameters	References
2005	Low latitude Malaysia	Investigate IONOS TEC, using dual frequency receiver at vertical height of 400 km	TEC data, Frequency rate *(0.5Hz)*	[20]
2008	Low latitude Malaysia	TEC variation according to height using IONEX data	TEC data, Heights and IONEX	[21]
2009	Low latitude Malaysia	Jones 3-D ray tracing method and Nequick international	TEC data, Elevation angle and height	[22]
2010	Low latitude Malaysia	Observation of TEC using a mapping function, leveling process and Matlab software	TEC data, F layer, Receiver Independent Exchange Format(RINEX) and pseudo-range	[29]
2010	Low latitude Malaysia	Single frequency commercial receiver used to stored GPS propagation data	Azimuth (φ), Elevation (θ), Signal to noise ratio(SNR), propagation time (t)	[2]
2011	Low latitude Malaysia	Evaluation of handheld GPS receiver data using mathematical model approach	Elevation angles, Azimuth, SNR and time	[5]

Year carried out	Region	Techniques / Model applied	Parameters	References
2012	Low latitude Hong Kong	Signal intensity SI can be calculated from the narrow band power (NBP) and wide band power (WBP)	Phase scintillation (σ_ϕ) and amplitude scintillation (S_4)	[26]
2012	Low latitude Malaysia	Using Handheld GPS receiver to evaluate signal strength	Azimuth (φ), Elevation (θ), Signal to noise ratio(SNR), propagation time (t)	[23]
2012	Low latitude Bhopal India	Rate of TEC (ROT)	TEC, GPS data Geomagnetic field	[30]
2012	Low latitude Africa (Cape Verde, Lagos and Kampal)	Rayleigh-Taylor, Algorithms by Gopi Seemala (GPS-TEC program)	S_4 index, TEC data, $F_{10.7}$ solar flux	[31]
2013	Low latitude Africa(Librevile, Mbarara and Malindi)	Linear least square, ROT and GPS-TEC program by Gopi	TEC data SYM-H index, receiver phase and code values	[27]
2013	Low latitude India	Ephemeris threat Models using message field range test	TEC data, scintillation index, elevation angle, azimuth angle and Carrier to Noise(C/N_o)	[28]

Table 2: Affected mobile satellite signal by ionospheric disturbances

Affected (MS)	Max S_4	Max σ_φ(radians)
PRN 08	0.87	1.14
PRN 12	0.97	0.79
PRN 14	0.68	0.71
PRN 15	1.08	0.38
PRN 17	0.63	0.60
PRN 18	0.69	0.09
PRN 21	0.63	0.13
PRN 25	0.79	0.27
PRN 27	0.62	1.03
PRN 29	0.78	0.26

2.2 Tec

GPS messages propagate through the ionosphere;the propagation velocity and direction of the GPS signal are changed in proportion due to the varying electron density along the line of sight (LOS) between the receiver and the satellite [1, 32–34]. The concentrated electrons effect the radio signal, by the time the signal reaches the receiver is equivalent to the integrated TEC, the quantity of electrons in a column stretching from the receiver to the satellite and the cross-sectional area of one square metre. This indeed affects the GPS range parameters; therefore a delay is attached to the code measurements and an increase to the phase observables. To achieve accurate and precise positioning from GPS system, these delays must be taken into account [35]. An in-depth studies of TEC variation for the ionosphere and a realistic forecast for the occurrence of 1 - 2 GHz frequency scintillations in the equatorial and low latitude F region using the GPS TEC data [36, 37].

The ionospheric effect on satellite navigation range measurements is highly variable. During a low solar activity period, the uncorrected ionosphere would typically cause vertical (zenith) field measurement delays from 1m at night to 5–10 m during the day. However, during peak periods of solar activity, the delay can vary from 1m at night to 100 m during the early afternoon [25]. Even more important from a navigational perspective is that there can be vast spatial slopes in the ionospheric effect on scale measurements. Depending on the class of the receiver used the gradient could cause meaningful positional errors. Ngwira [27] proposed a model of ionospheric effect due to the magnetic storm in the low-latitude region of some part of Africa where four GPS reference stations were used, and the presence of TEC fluctuation was computed given by higher values of ROT [29], [38] corresponds to the period of electron density depletion on. The computed data for the 13th to 15th September 2004 and gave the results as shown in Figure 4 for PRN 15 and PRN 24 in which the value of ROT is severely affected by ionospheric disturbances.

Total electron content prediction was made by Abdullah [29]utilizing the ionospheric data from Malaysia GISTM reference data station.

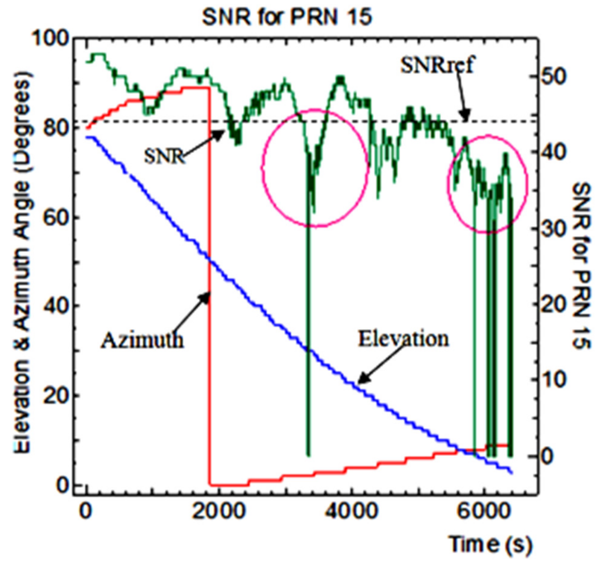


Figure 2: Signal for PRN

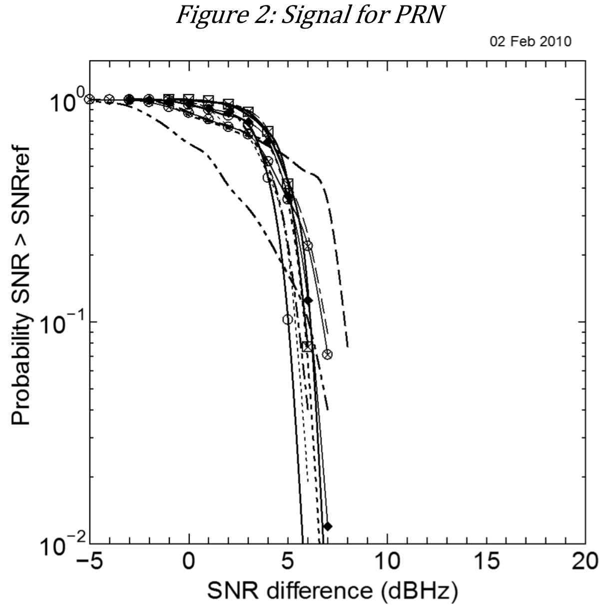


Figure 3 PRN CDF curve[5]

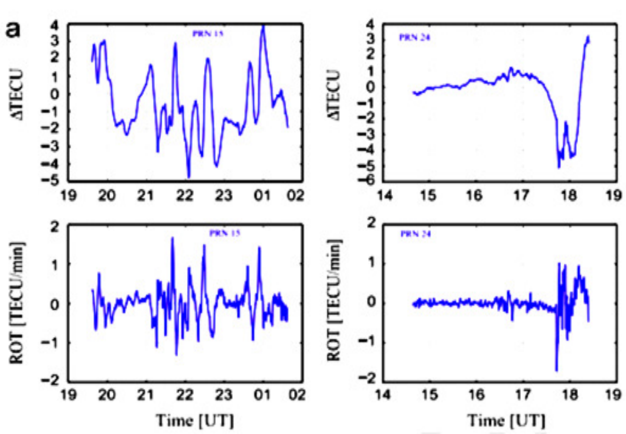


Figure 4: PRN 15 and PRN 24[27]

The ionospheric TEC measurement predicted the inherent fluctuations in pseudo-range and the TEC map shows variation of TEC from morning, noon, and afternoon. PRN 23 satellite signal observed the absolute ionospheric range error obtained due to group delay at two different stations within Malaysia. However, the prediction model[29] is limited only by GPS data available whereas the use of GALILEO and GLONASS data will enhance the accuracy of the prediction of the ionospheric TEC at low latitude region.

3. CONCLUSION

Mobile satellite signal performance is affected by several factors such as ionospheric effect, fading due to multipath and shadowing effect. These problems necessitate the need for experimental data in less developed and developing countries such as Asia, Africa and Latin America for the study and analysis of mobile satellite signal performance for communication purposes. Thus, experimental work is necessary to be carried out to investigate the effects and factors such as tree and building-shadowing on the signal strength.

The literature studies done cover some, but not all the studies conducted on ionospheric disturbances in the Low-latitude region in South East Asia, as well as Africa. Therefore, GPS technique of ionospheric models allows analysing different effects on the state of ionospheric disturbances. MS users particularly the GPS users should be cautious of the times and regions that have ionospheric disturbances such as active amplitude fading and phase scintillation effects. Furthermore, the available prediction models or services should be applied when a particular planning observation is made.

4. ACKNOWLEDGMENT

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